

PUBLISHED VERSION

Michael J. Chen, Yvonne M. Stokes, Peter Buchak, Darren G. Crowdy, Herbert T. C. Foo, Alastair Dowler, and Heike Ebendorff-Heidepriem

Investigation of oversized channels in tubular fibre drawing

Optical Materials Express, 2021; 11(3):905-912

DOI: <http://dx.doi.org/10.1364/OME.419607>

© 2021 Optical Society of America under the terms of the OSA Open Access Publishing Agreement. Users may use, reuse, and build upon the article, or use the article for text or data mining, so long as such uses are for non-commercial purposes and appropriate attribution is maintained. All other rights are reserved.

PERMISSIONS

https://www.osapublishing.org/submit/review/copyright_permissions.cfm#posting

Author and End-User Reuse Policy

OSA's policies afford authors, their employers, and third parties the right to reuse the author's Accepted Manuscript (AM) or the final publisher Version of Record (VoR) of the article as outlined below:

Reuse purpose	Article version that can be used under:		
	Copyright Transfer	Open Access Publishing Agreement	CC BY License
Posting by authors on an open institutional repository or funder repository	AM after 12 month embargo	VoR	VoR

Attribution

Open access articles

If an author or third party chooses to post an open access article published under OSA's OAPA on his or her own website, in a repository, on the arXiv site, or anywhere else, the following message should be displayed at some prominent place near the article and include a working hyperlink to the online abstract in the OSA Journal:

© XXXX [year] Optical Society of America]. Users may use, reuse, and build upon the article, or use the article for text or data mining, so long as such uses are for non-commercial purposes and appropriate attribution is maintained. All other rights are reserved.

When adapting or otherwise creating a derivative version of an article published under OSAs OAPA, users must maintain attribution to the author(s) and the published article's title, journal citation, and DOI. Users should also indicate if changes were made and avoid any implication that the author or OSA endorses the use.

29 June 2021

<http://hdl.handle.net/2440/130533>

Investigation of oversized channels in tubular fibre drawing

MICHAEL J. CHEN,¹ YVONNE M. STOKES,^{1,*}  PETER BUCHAK,²
DARREN G. CROWDY,³ HERBERT T. C. FOO,^{4,5} ALASTAIR
DOWLER,⁴ AND HEIKE EBENDORFF-HEIDEPRIEM^{4,5} 

¹*School of Mathematical Sciences, The University of Adelaide, Adelaide, South Australia 5005, Australia*

²*LowReTech LLC, 3401 Market St Suite 200, Philadelphia, PA 19104, USA*

³*Department of Mathematics, Imperial College London, 180 Queen's Gate, London, SW7 2AZ, UK*

⁴*Institute for Photonics and Advanced Sensing, School of Physical Sciences, The University of Adelaide, North Terrace, Adelaide, SA 5005, Australia*

⁵*ARC Centre of Excellence for Nanoscale BioPhotonics, The University of Adelaide, Adelaide, SA 5005, Australia*

*yvonne.stokes@adelaide.edu.au

Abstract: In a previous study, we compared experiments on drawing of axisymmetric tubular optical fibres to a mathematical model of this process. The model and experiments generally agreed closely. However, for some preforms and operational conditions, the internal channel of the drawn fibre was larger than predicted by the model. We have further investigated this phenomenon of an oversized channel with to determine the mechanism behind the size discrepancy. In particular we have explored the possibility of channel expansion similar to ‘self-pressurisation’ in fibres drawn from preforms that have been first sealed to the atmosphere, as previously described by Voyce et al. [*J. Lightwave Technol.* **27**, 871 (2009)]. For this, two pieces from each of two preforms with different inner to outer diameter ratios were drawn to fibre, one open to the atmosphere and the other with a sealed end. In addition, we have sectioned a cooled neck-down region from a previous experiment, for which the fibre had an oversized channel compared to the model prediction, and measured the cross-sectional slices. We here compare this new experimental data with the predictions of the previously derived model for drawing of an unsealed preform and a new model, developed herein, for drawing of a sealed tube. We establish that the observed oversized channels are not consistent with the self-pressurisation model for the sealed tube.

© 2021 Optical Society of America under the terms of the [OSA Open Access Publishing Agreement](#)

1. Introduction

Microstructured optical fibres (MOFs) are distinguished from solid optical fibres by the cross-sectional structure running along their length. The design of this cross-sectional structure gives the fibre certain optical and physical properties which are desirous in a range of applications (see, for instance, [1]). MOFs are fabricated by slowly feeding a preform of suitable geometry (typically 1–3 cm in diameter) into a heated region within a furnace and then stretching the softened glass to the dimensions of a fibre (typical outer diameters of 120–250 μm and internal channel diameters of the order of the wavelength of light). An operational challenge is to control the cross-sectional hole size in the fibre, and to this end mathematical models are used to predict how the preform geometry deforms as it is drawn.

We previously reported experiments on tubular fibre drawing over a range of operational conditions [2]. Using the ratio of inner to outer diameter, denoted ρ , to characterize the geometry of the tube, preforms of different diameter ratios ρ_0 were drawn to fibre, and the diameter ratio ρ_L of the final fibre was measured, as draw speed, furnace temperature, and active pressurisation were each systematically varied. Although the dimensions of the resulting fibres were generally

in agreement with recent models of the drawing process [3,4], in some cases, for which there was no active pressurisation of the channel, ρ_L was significantly larger than the model's prediction. This unexpected oversized channel phenomenon was more severe at higher draw speed, at higher pulling tension and for preforms with a relatively large diameter ratio ρ_0 . An example is 'Experiment 4' of [2]; for ease of reference the results for this experiment are reproduced in Fig. 1. In this case ρ_L was close to or greater than ρ_0 for all values of the pulling tension, although an oversized channel is simply defined to be a fibre diameter ratio exceeding the corresponding model prediction. Similar examples where, without any applied pressurisation, the relative size of channels in a fibre were larger than those in the corresponding preform, have previously been seen in the drawing of a seven-hole fluoride glass fibre [5] and a low-mode tellurite fibre [6]; see also the six-hole F2 glass preform shown in [2, Fig. 8].

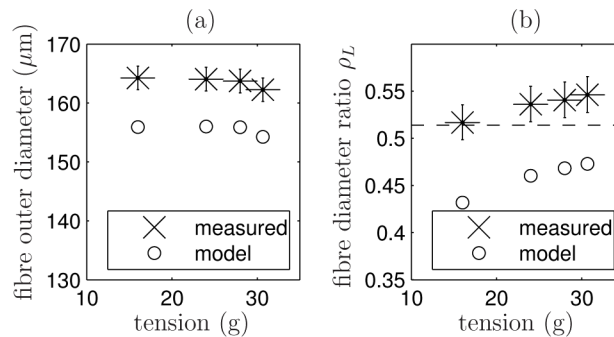


Fig. 1. Comparison between experimental measurements (crosses with error bars) and model output (circles) for 'Experiment 4' from [2]. Plotted against pulling tension are (a) the fibre outer diameter and (b) ρ_L , the diameter ratio of the fibre, with the diameter ratio of the preform, $\rho_0 = 0.514$, shown by the dashed line. No active channel pressurisation was used and the channel was open to the atmosphere. The preform outer diameter was 10 mm, the feed speed was 1.4 mm/min and the draw speed was 5.9 m/min.

We posited in [2] that the discrepancies between the model and the experiments might be due to an induced pressure in the channel and used a model for actively pressurised fibre drawing [4] to estimate the magnitude of this extra pressure. Voyce et al. [7] reported a modelling and experimental investigation of the drawing of a tubular preform with sealed ends, which prevents the escape of air and, so, deliberately induces a pressure in the air channel. The effect of sealing was termed 'self-pressurisation' and the mathematical model assumed a spatially constant pressure and negligible surface tension. That study showed excellent agreement between model and experiment; the observed diameter of the inner channel was slightly smaller than that predicted by the model, which is to be expected from the model's neglect of surface tension. Although the experiments in [2] were on unsealed tubes, the drawn fibres with the most severely oversized channels had a diameter ratio close to that of the preform. This suggested self-pressurisation because of the rapid reduction of the size of the channel cross-section through the neck-down during a draw or due to inadvertent sealing of the tube by some unidentified part of the apparatus.

The study of tubular fibres detailed in [2] is part of a larger project to investigate the fabrication of MOFs with the techniques of mathematical modelling [2–4,8–11]; this work demonstrates that measurement of pulling tension obviates the need to explicitly specify the viscosity profile along the neck-down region, and enables the modelling of MOF drawing for a sufficiently slender preform with any cross-sectional geometry (not just the capillaries in this study). Previous, less general, modelling of fibre drawing which did not have these features includes studies on drawing tubular preforms to fibre [12], on drawing MOFs which feature channels separated by thin struts

of glass [13] and validating the pressurised drawing of a six-hole preform against finite element simulations [14]. Other relevant modelling studies of related processes include modelling of solid fibre drawing with temperature dependence [15] and the drawing of thin glass sheets [16]. None of these previous studies have noted or addressed the phenomenon of oversized channels.

In this paper we provide detailed information on the oversized channel phenomenon for informing future modelling. In particular, we report on our investigations into self-pressurisation as the mechanism behind this phenomenon using tubular preforms with both small and large diameter ratio. In Section 2 we first briefly discuss the effects of surface tension and pressure in fibre drawing and then develop a new model applicable to drawing of sealed tubular fibres with channel pressurisation induced by sealing, which differs from that of [7] in including surface tension. In Section 3 we compare, using experiments and the models, fibre drawing of an unsealed tubular preform with that of an identical preform with a sealed end. In Section 4 we give more detailed information on the evolution of the cross-sectional shape over the neck-down region in the case of an oversized channel in the fibre, obtained from the cooled portion of the preform remaining after completion of ‘Experiment 4’ of [2]. Finally, in Section 5, we present our conclusions and discuss the direction of future modelling.

2. Effects of surface tension and pressure in fibre drawing

In the laboratory reference frame, fibre drawing is essentially a steady-state process and mass conservation requires that the ratio of the cross-sectional area S_0 at the start of the neck-down region ($x = 0$) to the cross-sectional area S_L at the end of the neck-down region ($x = L$) must equal the ratio of the draw speed U_{draw} to the feed speed U_{feed} (the draw ratio), i.e. $S_0/S_L = U_{\text{draw}}/U_{\text{feed}}$. In the absence of both surface tension and pressurisation of internal air channels, and where the cross-sectional length scale is much smaller than the neck-down length L , mathematical modelling has shown that the cross-sectional geometry of the fibre will differ from that of the preform only in size; however, relative to this case, surface tension will act to reduce the size of holes in the cross-section of the fibre while an internal pressure higher than atmospheric pressure will expand them.

For an axisymmetric tube with initial diameter ratio ρ_0 drawn to a fibre with diameter ratio ρ_L , this means $\rho_L = \rho_0$ in the absence of both channel pressurisation and surface tension, while $\rho_L < \rho_0$ for non-zero surface tension but no channel pressurisation, and $\rho_L > \rho_0$ for non-zero channel pressurisation but no surface tension. In the case of non-negligible surface tension and pressurisation, the magnitude of ρ_L relative to ρ_0 will depend on the relative strengths of the surface tension and the pressure. Let γ be the surface tension coefficient of the glass and p_H be the over-pressure above atmospheric pressure in the channel, where both are assumed to be constant. We also define

$$\alpha = \sqrt{\frac{1 - \rho}{\pi(1 + \rho)}} \quad (1)$$

where $\rho(x)$ is the diameter ratio of the cross-section at position x in the neck-down region and $\sqrt{S(x)}\alpha(x)$ is the wall thickness of the cross-section. Then, the model of [4] gives

$$\begin{aligned} \frac{\gamma}{2\sqrt{S}} - \frac{(1 - \pi^2\alpha^4)p_H}{8\pi\alpha} > 0 &\Rightarrow d\alpha/dx > 0 \Rightarrow d\rho/dx < 0, \\ < 0 &\Rightarrow d\alpha/dx < 0 \Rightarrow d\rho/dx > 0, \end{aligned} \quad (2)$$

and, since S reduces and curvature of the hole increases with x through the neck-down region, the effect of surface tension increases with x . From this it is apparent that if surface tension dominates pressure at $x = 0$ then this will be the case throughout the whole neck-down region so that $\rho_L < \rho_0$. However, in the case that pressure dominates surface tension at $x = 0$ then ρ will increase with x until S becomes sufficiently small that surface tension takes over as the dominant

effect, from which point ρ will decrease with x . In this latter case ρ_L may be larger than, smaller than, or equal to ρ_0 depending on if and when this happens.

We now consider what happens when the pressure p_H is due to self-pressurisation because the ends of the tube are sealed so there can be no flux of air into or out of the tube. Following [7], we assume the air to be an ideal gas and the pressure p_H to be spatially uniform throughout the channel. Then, at any two positions x_1 and x_2 along the length of the preform-fibre, the air temperature T and density δ must satisfy (using subscripts to denote the position) $\delta_1/\delta_2 = T_2/T_1$. Moreover, our steady-state approximation requires that, as with the glass, the air flux be the same at every position x . Now, under steady-state conditions, sufficiently far above the neck-down region the air temperature and density are constant values, T_{top} , δ_{top} , respectively, and the air, necessarily, moves with the glass because the tube is sealed. Similarly, sufficiently far below the neck-down region, where the tube has the dimensions of the final fibre and has cooled completely, we assume that the air temperature and density attain constant values T_{bot} , δ_{bot} and, again, the air must move with the glass because the tube is sealed. Then, for a preform and fibre with external radii R_0 and R_L , respectively, $\pi R_0^2 \rho_0^2 \delta_{\text{top}} U_{\text{feed}} = \pi R_L^2 \rho_L^2 \delta_{\text{bot}} U_{\text{draw}}$. Noting that area $S = \pi R^2(1 - \rho^2)$ for a cross-section of external radius R and diameter ratio ρ , we use the relationship between the draw ratio and the cross-sectional areas of the preform and fibre to obtain, after some manipulation,

$$\rho_L^2 = \frac{\rho_0^2}{\delta_{\text{bot}}/\delta_{\text{top}} + \rho_0^2(1 - \delta_{\text{bot}}/\delta_{\text{top}})}. \quad (3)$$

Since the top of the preform above the neck-down region must be at least as hot as the room-temperature fibre far below the neck-down region, $T_{\text{top}}/T_{\text{bot}} = \delta_{\text{bot}}/\delta_{\text{top}} \geq 1$ so that, from Eq. (3), $\rho_L \leq \rho_0$. Therefore, assuming the validity of the assumptions of the self-pressurisation model, in a sealed tube the diameter ratio of the fibre will be no larger than that of the preform. From the discussion above we know that either the (self) pressure p_H will be sufficiently small relative to surface tension that ρ will decrease for all $x \in [0, L]$, or p_H will be sufficiently large that ρ will increase with x for $0 \leq x < x_C$ for some $x_C < L$, from which point $S(x)$ will have reduced sufficiently that surface tension will dominate pressure and ρ will reduce for $x_C < x \leq L$. Either way the outcome will be $\rho_L \leq \rho_0$.

Because we expect the temperature at the top of the preform and that of the drawn fibre to be (nearly) equal for much of the fibre draw when the process is essentially steady, we will plot model results for self-pressurisation assuming $T_{\text{top}}/T_{\text{bot}} = 1$, yielding the prediction $\rho_L = \rho_0$. However, all experimental results satisfying $\rho_L \leq \rho_0$ will be deemed consistent with this model.

3. Comparison between an unsealed and sealed tube

In [2] we reported on six experiments of drawing unsealed tubular preforms to fibre. The first two of these experiments (labelled ‘Experiment 1’ and ‘Experiment 2’ in [2]) involved tubes of 10 mm outer diameter and 1.6 mm inner diameter, with fixed feed and draw speeds ($U_{\text{feed}} = 1.4$ mm/min, $U_{\text{draw}} = 5.8$ m/min) and a furnace temperature (T_{furnace}) which was varied between 940°C and 880°C. The two experiments exhibited slightly different behaviour, and the second experiment closely matched the model predictions of [3]. The discrepancy between these experiments motivates a third replication of this experiment in the present study.

For this third repetition an extruded F2-glass tube of 10 mm outer diameter and 1.7 mm inner diameter was drawn to fibre with the operational parameters stated above; we denote the ratio between the inner and outer diameters of the preform $\rho_0 = 0.17$. The surface tension parameter for F2 glass is $\gamma = 0.23$ Nm⁻¹ [17] (which is assumed to be constant over the small temperature range used in these experiments) and the neck down length was $L = 0.03$ m. We apply the fibre drawing model for annular tubes from [3] to this new experiment, and then compare the diameter

ratio of the fibre yielded by the model to measurements of the drawn fibre. Fig. 2(a) shows the fibre diameter ratio ρ_L of the fibre against pulling tension as given by both experiment and model, where pulling tension increases as furnace temperature is lowered. There is close agreement between the model and the experiments across all four pulling tensions, corroborating the results of ‘Experiment 2’ from [2] which similarly matched the model. ‘Experiment 1’ from [2], which showed inexplicably different results, is henceforth discarded as erroneous.

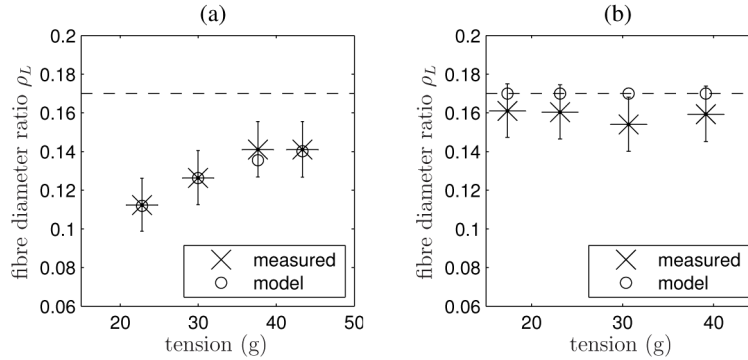


Fig. 2. Comparison between experimental measurements (crosses with error bars) and model output (circles) for the preform with diameter ratio $\rho_0 = 0.17$. Plotted against the pulling tension is the fibre diameter ratio ρ_L for the (a) unsealed preform and (b) sealed preform, with ρ_0 shown by the dashed line.

To establish how the self-pressurisation effect described in Section 2 manifests under operational conditions similar to those used in the experiments described above, a sealed tube was also drawn to a fibre. The preform was nearly identical to that used in the unsealed experiment and, in fact, both these preforms were short sections (around 17 cm long) of one longer extrusion. In this case, the top end was sealed by filling the first few millimetres of the channel with epoxy resin, while the fibre was drawn from the lower end (it being assumed that the diameter of the channel through the drawn fibre was so small that the preform was effectively sealed at the bottom). The operational parameters were identical to those used in the unsealed experiment. The diameter ratio for the sealed-tube draw is shown in Fig. 2(b). Both model and experiment agree in showing this to be essentially independent of pulling tension with the experiment showing ρ_L to be a little smaller than ρ_0 which is consistent with the model.

Noting that the most severe cases of oversized channels in [2] correspond to the experiments on preforms with large diameter ratio (see Fig. 1 above where $\rho_L > \rho_0$), an experiment similar to those just described was also performed for both unsealed and sealed preforms with large diameter ratio. Specifically, each preform had nominal outer and inner diameters of 10 mm and 6 mm, respectively, such that $\rho_0 = 0.61$. Fig. 3 compares the experimental measurements with the relevant model for the unsealed and sealed preforms, respectively. In both cases we see a large difference between the model and experiment with ρ_L exceeding ρ_0 by a significant amount which is not consistent with either model. Moreover, there is little difference between the sealed and unsealed tubes. A comparison of the results in Fig. 3 for the unsealed preform with Fig. 1 also shows the difference between model and experiment to be larger for larger diameter ratio.

In summary, the experimental results for the preforms with small diameter ratio $\rho_0 = 0.17$ agree with the models, showing a marked difference between the sealed tube, where ρ_L is just a little less than ρ_0 and is independent of pulling tension, and the unsealed tube, where ρ_L is significantly less than ρ_0 and changes with pulling tension. For the preforms with large diameter ratio $\rho_0 = 0.61$ there is poor agreement with the models and a similar outcome for both sealed and unsealed preforms, namely oversized holes with ρ_L substantially larger than ρ_0 and little

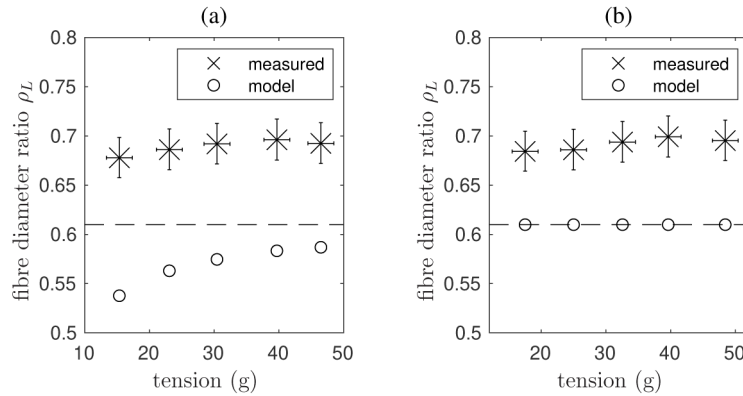


Fig. 3. Comparison between experimental measurements (crosses with error bars) and model output (circles) for the preform with diameter ratio $\rho_0 = 0.61$. Plotted against pulling tension is the fibre diameter ratio ρ_L for the (a) unsealed preform and (b) sealed preform, with ρ_0 shown by the dashed line.

dependence on pulling tension. This suggests that the phenomenon of oversized holes is not simply explained by self-pressurisation of the channel caused by the rapid reduction in the size of the channel or inadvertent sealing by some unidentified part of the draw apparatus.

4. Investigation of geometry through a tubular neck-down

Although the preform neck-down remaining at the conclusion of a fibre drawing experiment may deform slightly as it cools, it is likely that the geometry of the cooled neck-down is representative of the geometry in the neck-down during fibre drawing. Assuming this we examined the exact shape along the length of a cooled neck-down to assist with identification of the mechanism leading to the phenomenon of oversized channels. Since ‘Experiment 4’ of [2], which used an unsealed preform with diameter ratio $\rho_0 = 0.514$, showed a pronounced oversizing of the diameter ratio relative to the model prediction (see Fig. 1), we selected the remainder of this preform for detailed examination.

This neck-down was sectioned into 1 mm cross-sectional slices. First the neck-down was encased in epoxy resin and then sliced from the end with largest diameter using a high precision glass saw. The newly cut end was polished after each slice was cut off. Measurements were made of the inner and outer diameters of the polished side of each slice, and their ratio ρ was computed. These measurements are shown in Figs. 4(a) and (b), where $x = 0$ corresponds to the first slice. The sectioned length was around 15 mm of the neck-down, which had a total length of around 30 mm. Part of the extremely fragile fibre end had snapped off prior to sectioning. The gap in the data at 10 mm is where a slice cracked during this delicate sectioning process.

The results for the cross-sectional measurements of ρ , shown in Fig. 4(b), display some unexpected behaviour. For the initial 5 mm of the neck-down ρ is within measurement error of the preform. Beyond this ρ decreases to 0.34 at $x = 13$ mm and then increases sharply to $\rho = 0.46$ at the last measurement position, $x = 15$ mm. The fibre that corresponds most closely to this neck-down was that obtained at the end of the experiment using the final pulling tension value of 30 g (see results in Fig. 1(b) above and [2] for details on the experimental procedure) having $\rho_L = 0.546$, which is larger than the diameter ratio of 0.46 for the last measured point of the neck-down. This implies that ρ continued to increase beyond the last measurement position. This behaviour is surprising and not explained by any model of fibre drawing developed to date. As discussed in Section 2, the model of [4] shows that in the absence of internal pressure, ρ must decrease along the neck-down due to surface tension. On the other hand, with pressurisation of

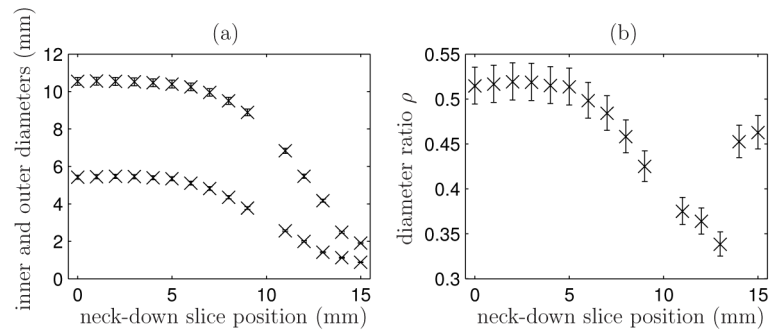


Fig. 4. Geometry through the upper 15 mm of the cooled neck-down region remaining after ‘Experiment 4’ of [2], where $x = 0$ mm corresponds to the first slice at the end with largest diameter and $x = 15$ mm corresponds to the last slice. (a) Physical external and internal diameters, and (b) the inner to outer diameter ratio ρ . The value of ρ at $x = 0$ compares with the diameter ratio of the initial preform, $\rho_0 = 0.514$.

the internal channel, either surface tension dominates pressure for all time, and ρ must decrease with distance along the neck-down, or pressure initially dominates surface tension, and ρ will initially increase and then decrease when the cross-sectional area reduces (due to stretching) sufficiently that surface tension becomes dominant. Neither of these behaviours correspond to that shown in Fig. 4(b), where ρ decreases before a sharp increase as the neck-down radius approaches fibre dimensions. Thus, this analysis adds to the evidence that self-pressurisation is not the mechanism for oversized air channels in fibres.

5. Conclusions

We have developed a new steady-state model for drawing of a sealed preform, where both an induced pressure in the channel due to sealing and surface tension are important, and have performed several targeted experiments to explore self-pressurisation as the mechanism behind the phenomenon of oversized channels seen in the drawing of some preforms to fibre. Relevant models together with experiments using tubular preforms of small diameter ratio, agree and show the behaviour of sealed and unsealed tubes to be markedly different. For the former self-pressurisation results in a fibre with diameter ratio comparable to, and not larger than, that of the preform; for the latter the fibre diameter ratio is significantly smaller than that of the preform. New experiments on unsealed and sealed preforms with larger diameter ratio, yielded similar fibres with diameter ratio significantly larger than the preform in both cases. In neither case did the outcome correspond with the relevant model. This shows that oversized channels are not explained by self-pressurisation. The sectioning of a cooled neck-down from an experiment that yielded a fibre with a significantly oversized channel also revealed a profile through the neck-down that is inconsistent with inflation due to a uniform pressure in the channel arising from self-pressurisation.

Although eliminating self-pressurisation as the mechanism for oversized channels in fibres drawn from unsealed preforms, our experiments also suggest an alternative cause that warrants future investigation. Noting that oversized channels depend on both preform geometry and furnace temperature which controls pulling tension, and that the neck-down sectioning revealed expansion immediately after the region of rapid change in the diameter, hence viscosity, we will investigate 3D effects due to a sharp neck-down as the cause of apparently oversized geometry and the influence on this of temperature/viscosity gradient through the neck-down.

Funding. Australian Research Council (DP130101641, FT160100108); Leverhulme Trust; Australian National Fabrication Facility.

Acknowledgments. We thank Jeremy Wong, Alson Kwun Leung Ng and Minh Hoa Huynh, University of Adelaide, for assistance with experiments.

This research was supported by grants DP130101541 and FT160100108 from the Australian Research Council and by a Research Grant from the Leverhulme Trust. It was in part performed at the Optofab node of the Australian National Fabrication Facility utilising Commonwealth and SA State Government funding.

Disclosures. The authors declare no conflicts of interest.

References

1. T. M. Monro and H. Ebendorff-Heidepriem, "Progress in microstructured optical fibers," *Annu. Rev. Mater. Res.* **36**(1), 467–495 (2006).
2. M. J. Chen, Y. M. Stokes, P. Buchak, D. G. Crowdy, H. T. C. Foo, A. Dowler, and H. Ebendorff-Heidepriem, "Drawing tubular fibres: experiments versus mathematical modelling," *Opt. Mater. Express* **6**(1), 166–180 (2016).
3. Y. M. Stokes, P. Buchak, D. G. Crowdy, and H. Ebendorff-Heidepriem, "Drawing of micro-structured fibres: circular and non-circular tubes," *J. Fluid Mech.* **755**, 176–203 (2014).
4. M. J. Chen, Y. M. Stokes, P. Buchak, D. G. Crowdy, and H. Ebendorff-Heidepriem, "Microstructured optical fibre drawing with active channel pressurisation," *J. Fluid Mech.* **783**, 137–165 (2015).
5. H. Ebendorff-Heidepriem, T.-C. Foo, R. C. Moore, W. Zhang, Y. Li, T. M. Monro, A. Hemming, and D. G. Lancaster, "Fluoride glass microstructured optical fiber with large mode area and mid-infrared transmission," *Opt. Lett.* **33**(23), 2861–2863 (2008).
6. H. Ebendorff-Heidepriem, R. C. Moore, and T. M. Monro, "Progress in the fabrication of the next-generation soft glass microstructured optical fibers," *AIP Conference Proceedings* **105**, 95–98 (2008).
7. C. J. Voyce, A. D. Fitt, J. R. Hayes, and T. M. Monro, "Mathematical modeling of the self-pressurizing mechanism for microstructured fiber drawing," *J. Lightwave Technol.* **27**(7), 871–878 (2009).
8. P. Buchak, D. G. Crowdy, Y. M. Stokes, and H. Ebendorff-Heidepriem, "Elliptical pore regularization of the inverse problem for microstructure optical fibre fabrication," *J. Fluid Mech.* **778**, 5–38 (2015).
9. H. Tronnolone, Y. M. Stokes, H. T. C. Foo, and H. Ebendorff-Heidepriem, "Gravitational extension of a fluid cylinder with internal structure," *J. Fluid Mech.* **790**, 308–338 (2016).
10. M. J. Chen, Y. M. Stokes, P. Buchak, D. G. Crowdy, and H. Ebendorff-Heidepriem, "Asymptotic modelling of a six-hole MOF," *J. Lightwave Technol.* **34**(24), 5651–5656 (2016).
11. Y. M. Stokes, J. J. Wylie, and M. J. Chen, "Coupled fluid and energy flow in fabrication of microstructured optical fibres," *J. Fluid Mech.* **874**, 548–572 (2019).
12. A. D. Fitt, K. Furusawa, T. M. Monro, C. P. Please, and D. J. Richardson, "The mathematical modelling of capillary drawing for holey fibre manufacture," *J. Eng. Math.* **43**(2/4), 201–227 (2002).
13. G. T. Jasion, J. S. Shrimpton, Y. Chen, T. Bradley, D. J. Richardson, and F. Poletti, "Microstructure element method (MSEM): viscous flow model for the virtual draw of microstructured optical fibers," *Opt. Express* **23**(1), 312–329 (2015).
14. G. Luzi, P. Eppe, M. Scharrer, K. Fujimoto, C. Rauh, and A. Delgado, "Numerical solution and experimental validation of the drawing process of six-hole optical fibers Including the effects of inner pressure and surface tension," *J. Lightwave Technol.* **30**(9), 1306–1311 (2012).
15. M. Taroni, C. Breward, L. Cummings, and I. M. Griffiths, "Asymptotic solutions of glass temperature profiles during steady optical fibre drawing," *J. Eng. Math.* **80**(1), 1–20 (2013).
16. D. O'Kiely, C. J. W. Breward, I. M. Griffiths, P. D. Howell, and U. Lange, "Edge behaviour in the glass sheet redraw process," *J. Fluid Mech.* **785**, 248–269 (2015).
17. K. Boyd, H. Ebendorff-Heidepriem, T. M. Monro, and J. Munch, "Surface tension and viscosity measurement of optical glasses using a scanning CO₂ laser," *Opt. Mater. Express* **2**(8), 1101–1110 (2012).